CORPS OF ENGINEERS, U. S. ARMY

TIDAL FLUSHING OF ESTUARIES

REPORT NO. 1

PROPOSED PROGRAM OF INVESTIGATIONS FOR FISCAL YEARS 1953 AND 1954

TECHNICAL MEMORANDUM NO. 2-374

PREPARED FOR

OFFICE, CHIEF OF ENGINEERS

BY

WATERWAYS EXPERIMENT STATION

VICKSBURG, MISSISSIPPI

APRIL 1953

(REVISED DECEMBER 1953)

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
APR 1953		**00-00-1953 to 00-00-1953**

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Tidal Flushing of Estuaries: Report No. 1: Proposed Program of Investigations for Fiscal Years 1953 and 1954	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **U.S. Army Corps of Engineers,Waterway Experiment Station,3903 Halls Ferry Road,Vicksburg,MS,39180**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a REPORT **unclassified**	b ABSTRACT **unclassified**	c THIS PAGE **unclassified**	**Same as Report (SAR)**	**16**	

Preface

This report is the first of a series of reports on the investigation of Tidal Flushing of Estuaries, being conducted by the Waterways Experiment Station for the Office, Chief of Engineers, and sponsored jointly by Military Operations and Civil Works. The investigation was authorized by the Office, Chief of Engineers, on 16 December 1952.

This present report contains the details of the program of investigations proposed for Fiscal Years 1953 and 1954 which were discussed and agreed upon during conferences with consultants held at the Waterways Experiment Station on 11-12 February 1953. Subsequent to the conference, more detailed and specific comments on the proposed program have been obtained from the consultants and have been included in the proposed program contained in this report.

The report consists of a main report and one appendix. The main report outlines the objectives of the investigation, the program of model tests considered essential for attainment of the objectives, and a discussion of instrumentation requirements. Appendix A contains the minutes of conferences with consultants held at the Waterways Experiment Station on 11-12 February 1953.

A list of the reports published to date in connection with this investigation is printed on the inside of the front cover of each report for the information of the reader.

Contents

TIDAL FLUSHING OF ESTUARIES

PROPOSED PROGRAM OF INVESTIGATIONS FOR FISCAL YEARS 1953 AND 1954

Introduction

1. This report presents the details of the program of investigations proposed for Fiscal Years 1953 and 1954 relative to the study of tidal flushing of estuaries. The objectives of this program of investigations are:

a. To explore the basic fundamentals of tidal flushing of estuaries in an attempt to develop accurate analytical methods for determining the flushing characteristics of those estuaries being maintained for navigation or other purposes by the Corps of Engineers. The purposes of this phase of the investigation are (1) to permit reasonably accurate computation of the dispersion, dilution, or accumulation of contaminating agents introduced into estuaries by natural or man-made processes, and (2) to permit accurate computation of the effects of proposed changes in the physical characteristics of estuaries on their flushing characteristics.

b. To obtain sufficient empirical data from existing hydraulic models of important estuaries to provide (1) an interim analysis of the flushing characteristics of those important estuaries for which existing hydraulic models are available, and (2) a means for quickly evaluating the effects of salinity distribution, fresh-water discharge, tidal range, location of release of contaminant, dimensions of contaminated area, and possibly other physical and hydraulic features on the flushing characteristics of such estuaries.

Tentative Model Test Program

2. The program of model tests tentatively planned to attain the objectives of the investigation is divided into two phases: (a) tests required for development of analytical methods for computing the flushing characteristics of any estuary for which such information is desired; and (b) tests in existing hydraulic models of specific estuaries to provide an interim analysis of their flushing characteristics, and to provide

means for evaluating the accuracy of analytical methods developed under phase (a). The tests agreed upon as being the minimum program required to attain these objectives are described in detail in the following paragraphs. In addition, discussions pertaining to instrumentation and techniques to be employed during the model test program, which are considered sufficiently important to make of record, are summarized herein.

Tests required for development of analytical flushing equations

3. This test program will be carried out in two flumes already in existence at this office, both of which are connected to basins of substantial size in which tidal amplitudes and periods can be easily controlled. One flume is constructed of lucite and is 150 ft long (soon to be extended to about 325 ft), 0.75 ft wide, and 1.5 ft deep. The other is constructed of concrete and is 150 ft long, 10 ft wide, and 1.5 ft deep. Both flumes are equipped for the introduction and measurement of fresh-water inflows and measurement of water-surface profiles, salinities, current velocities, and other pertinent phenomena.

4. It is thought that the most important dynamic feature of estuaries with respect to flushing is that of stratification. At one extreme is the almost completely stratified estuary, such as the Lower Mississippi River, while at the other extreme is the almost completely mixed estuary such as the Raritan River. Other estuaries throughout this country are known to exhibit degrees of stratification somewhere between the two extremes cited above. For the purpose of this investigation it is planned to investigate at least four degrees of stratification as follows:

a. Completely stratified -- similar to the Lower Mississippi River and referred to hereinafter as Type 1.

b. Partly stratified -- similar to Savannah Harbor, Georgia, and referred to hereinafter as Type 2.

c. Partly stratified -- similar to the Delaware River and referred to hereinafter as Type 3.

d. Completely mixed -- similar to the Raritan River but possibly more completely mixed and referred to hereinafter as Type 4.

If it should become necessary during the investigation to classify

estuaries by types in order to develop separate analytical methods for computing flushing characteristics for each type, it is thought that classification in terms of degree of stratification would be most feasible.

5. Tests in lucite flume. The testing program planned for the lucite flume is designed to provide most of the basic data needed for development of analytical methods for computing flushing characteristics of estuaries. This program is outlined below.

a. Tests to determine effects of stratification on flushing characteristics (total of 18 tests). Fresh-water discharges will be adjusted to produce a constant length of salinity intrusion of about 100 ft for all types of stratification. Tidal amplitudes and periods will be varied as needed to produce desired type of stratification.

(1) Type 1 stratification:

Test 1 will involve release of contaminant as a column extending from surface to bottom upstream from tip of salt-water wedge.

Test 2 will be identical with test 1 except that contaminant will be released at tip of wedge.

Test 3 will be identical with test 1 except that contaminant will be released one-third of wedge length downstream from tip of wedge.

Test 4 will be identical with test 3 except that contaminant will be released only in fresh water above wedge interface instead of throughout depth.

Test 5 will be identical with test 4 except that contaminant will be released only in salt water below interface.

Tests 6, 7, and 8 will be identical with tests 3, 4, and 5 except that contaminant will be released at point two-thirds of wedge length downstream from tip of wedge.

(2) Type 2 stratification:

Tests 9 through 16 to be conducted identically with tests 1 through 8 for Type 1 stratification.

(3) Type 3 stratification:

Test 17 will be identical with test 3 for Type 1 stratification.

(4) Type 4 stratification:

Test 18 will be identical with test 3 for Type 1 stratification.

b. Tests to determine effects of tidal amplitude on flushing characteristics, using Type 3 stratification only (total of 3 tests).

(1) Test 19 will be made for tidal amplitude of 0.05 ft, tidal period of 5 minutes, fresh-water discharge as required to produce intrusion length of about 100 ft in flume, and metal strip roughness as required to produce mean bottom salinities about 50 per cent in excess of mean surface salinities. Contaminant will be released as column extending from surface to bottom at point one-third intrusion length downstream from tip of intrusion.

(2) Test 20 will be identical with test 19 except that tidal amplitude will be increased to 0.1 ft. No change from test 19 roughness or fresh-water discharge.

(3) Test 21 will be identical with test 19 except that the tidal amplitude will be increased to 0.2 ft. No change from test 19 roughness or fresh-water discharge.

6. Tests in concrete flume. The testing program (total of 13 tests) for the concrete flume is designed to provide data as to possible scale effects in transferring model flushing data to the prototype, to determine the effects of geometry of an estuary on its flushing characteristics, and to determine the effects of river discharge for well-defined geometric shape of estuary. The program for the concrete flume is outlined below.

a. Tests to determine possible scale effects in transferring model flushing data to the prototype (Types 1 and 3 stratification):

(1) Tests 1-8 (Type 1 stratification). Using full length, width, and depth of concrete flume, stratification will be checked against that observed in lucite flume for Type 1 stratification. Metal strip roughness will be used if required to duplicate Type 1 stratification as observed in lucite flume. Tests 1-8 in concrete flume to be identical with tests 1-8 in lucite flume. Results will be checked for possible scale effects.

(2) Test 9 (Type 3 stratification). Procedure described above will be duplicated to attain Type 3 stratification in concrete flume identical to that observed in lucite flume. Test 9 will be identical with test 17 in lucite flume. Results will be checked for possible scale effects.

b. Tests to determine the effects of geometry of an estuary on its flushing characteristics (Type 3 stratification):

(1) Test 10 will involve tapering the concrete flume from 10 ft wide at tidal basin end to 1.0 ft wide at

opposite end. Test 9 will be duplicated except fresh-water discharge will be reduced by 90 per cent from that of test 9.

(2) Test 11 will involve tapering the concrete flume from 10 ft wide at tidal basin end to 4.5 ft wide at opposite end. Test 9 will be duplicated except fresh-water discharge will be reduced by 55 per cent from that of test 9.

c. Tests to determine effects of river discharge on flushing characteristics for conditions of well-defined geometric shape of estuary.

(1) Tests 12 and 13 will be identical with test 10 except test 12 will involve increasing the fresh-water discharge of test 10 by a factor of two, and test 13 will involve increasing the fresh-water discharge by a factor of four.

Tests in existing models

7. Existing models of Delaware River and Charleston Harbor were selected for this series of tests. In addition, models of the Raritan River, New Jersey, and Grays Harbor, Washington, are available for tests if it is found desirable to increase the scope of this program to cover a wider field of estuary types. Models of San Francisco Bay, California, and Savannah Harbor, Georgia, are planned for the near future, and it would probably be very desirable to conduct flushing tests in these models when and if they are available for such tests. The Delaware River and Charleston Harbor models were selected for the tests described herein since they are typical harbors and represent different types of estuaries as to stratification, geometry, etc.

8. Delaware River model. A total of 25 flushing tests is planned for the Delaware River model, as outlined below. Factors to be investigated consist of location of contamination, size of contaminated area, tidal amplitude, fresh-water discharge, concentration of contamination, and tidal plane.

a. Effects of location of contamination (tests 1-3). Tests 1-3 will be made for conditions of mean tide, mean fresh-water discharge, mean size of contaminated area, and mean tidal plane. Contamination will be released near Philadelphia (upstream from limit of salinity intrusion), near Chester Island (at about limit of salinity intrusion), and near Artificial Island (in salt-water section). These locations will be referred to hereinafter as upstream, intermediate,

and downstream locations for release of contamination.

b. Effects of size of contaminated area (tests 4 and 5). These tests will be made for the upstream area for release of contamination; all other test conditions will be the same as for tests 1-3. Test 4 will involve contaminating a 2,000-ft (prototype) length of the channel, while test 5 will involve contaminating a 10,000-ft length of the channel. Test 1 will involve contaminating a 6,000-ft length of channel, so data for these sizes of contaminated area will be available for comparison.

c. Effects of tidal amplitude (tests 6-11). Tests 6-8 will be made for spring tide conditions, and tests 9-11 for neap tide conditions. Tests 6-8, respectively, and 9-11, respectively, will involve release of contamination at upstream, intermediate, and downstream locations. Mean fresh-water discharge, mean concentration of contaminant, and mean size of contaminated area will be used for all tests. Tests 1-3 will provide comparable data for mean tide conditions, so results for these conditions of tide will be available for comparison.

d. Effects of fresh-water discharge (tests 12-17). Tests 12-14 will be made for conditions of low fresh-water discharge (about 5,000 cfs at and including the Schuylkill River), and tests 15-17 will be made for high fresh-water discharge (about 40,000 cfs at and including the Schuylkill River). Tests 12-14, respectively, and 15-17, respectively, will involve release of contaminant from upstream, intermediate, and downstream locations. Other test conditions will involve mean concentration of contamination, mean size of contaminated area, and mean tides.

e. Effects of concentration of contamination* (tests 18-23). Tests 18-20 will be made for an initial concentration of contamination of about 1,000 ppm, and tests 21-23 will be made for an initial concentration of about 4,000 ppm (mean concentration is about 2,500 ppm). Tests 18-20, respectively, and 21-23, respectively, will involve release from upstream, intermediate, and downstream locations. Other test conditions will consist of mean tide, mean fresh-water discharge, and mean size of contaminated area. Tests 1-3 will provide comparable data for mean concentration, so data for three conditions will be available for comparison.

f. Effects of tidal plane (tests 24 and 25). Test 24 will involve lowering the tidal plane about 5 ft, and test 25 will involve raising the tidal plane about 5 ft. Other test

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* Concentrations of contamination stated in the test program are tentative and are only for the purpose of planning tests on a comprehensive basis. Absolute concentrations used will depend on instrumentation requirements, the nature of the selected contamination, and other factors.

conditions will consist of mean tide, mean fresh-water discharge, mean concentration of contamination, and mean size of contaminated area. Tests 24 and 25 will involve release of contamination at upstream location only. Test 1 will provide comparable data for mean tidal plane, so data for three conditions will be available for comparison.

9. Charleston Harbor model. A total of nine flushing tests is tentatively planned for the Charleston Harbor model; the factors to be investigated consist of location for release of contamination and tidal amplitude. However, if the results of tests in the Delaware River model indicate that other factors are of major rather than minor importance (effect of concentration, effect of size of contaminated area, effect of tidal plane, etc.), it may be necessary to increase the scope of tests in the Charleston Harbor model. The program of tests now contemplated in this model is outlined below.

a. Effects of location for release of contamination (tests 1-3). The three areas selected for release of contamination in the Charleston Harbor model are near the upstream end of the navigation project, just upstream from Drum Island, and near Ft. Sumpter. These locations are referred to hereinafter as the upstream, intermediate, and downstream locations for release of contamination. Tests 1-3, respectively, will involve release from the upstream, intermediate, and downstream locations. Other test conditions will consist of mean tide, mean fresh-water discharge, an initial concentration of contamination of about 2,500 ppm, and an area of contamination covering about 6,000 ft (prototype) of the channel.

b. Effects of tidal amplitude (tests 4-9). Tests 4-6, respectively, and 7-9, respectively, will involve release of contamination from the upstream, intermediate, and downstream locations. Tests 4-6 will be made for neap tide conditions, and tests 7-9 will be made for spring tide conditions. Other test conditions will be identical with those of tests 1-3. Tests 1-3 will provide comparable data for mean tide conditions, so data for the three conditions will be available for comparison.

Testing Techniques and Instrumentation

10. The tracer used to represent contamination during previous tests in the Delaware River model was methylene blue chloride, and measurements of concentraction were made with spectrophotometers. The methylene

blue chloride proved to be an excellent tracer from the viewpoint of determining concentration easily and accurately; however, its tendencies toward absorption into the model bed and adsorption to the model, sample jars, and other equipment with which it came into contact required use of correction factors to compensate for loss during the course of the tests. Attempts will be made to locate a tracer having the same good qualities as methylene blue chloride but without the adverse qualities of high rates of absorption and adsorption. If such a tracer cannot be found, attempts will be made to decrease the absorption and adsorption rate of methylene blue chloride by changing the pH of the water in the models (the natural pH is such as to coincide with the peak absorption and adsorption rates for methylene blue chloride).

11. Measurements of tracer concentration during previous tests in the Delaware River model were made by obtaining samples from the model at selected points and times and determining concentrations with spectrophotometers. This procedure was adequate for the previous tests, but it required the use of a large number of model operators (up to a total of 10 for some tests). Inasmuch as it is desired to obtain more complete data during tests contemplated for the present investigation, it is believed that the former procedure should be abandoned and instruments developed for "in place" measurement and recording of tracer concentrations. The type of instrument visualized would consist of a very small photoelectric cell and light source that could be submerged in the model without interfering with flow characteristics, connected to an automatic recorder to obtain continuous records of tracer concentration. It is believed that development of such an instrument can be accomplished within a reasonable period of time, and that use of about 10 such instruments will provide very complete data for the flushing tests contemplated. Development and construction of the 10 instruments are estimated to cost about $8,000 to $10,000; however, since their use will reduce the requirements for model operators to a minimum, the saving in labor costs for the testing program contemplated will more than offset the cost of development and construction of the instruments. In addition, much more complete data can be obtained with the instruments than was possible with the labor force used during previous flushing tests in the Delaware River model.

Appendix A

Report of Conferences with Consultants on Tidal Flushing of Estuaries

1. This report presents a resume of conferences with consultants held at the Waterways Experiment Station on 12 and 13 February 1953 for the purpose of outlining detailed methods, techniques, and test programs required for attainment of the objectives of the investigation of flushing of estuaries recently assigned to this office. Those in attendance at the conferences were:

Consultants

Dr. A. T. Ippen, M.I.T.
Dr. A. B. Arons, Amherst College
Dr. D. W. Pritchard, Chesapeake Bay Institute

Waterways Experiment Station Personnel

Col. C. H. Dunn, Director
Mr. J. B. Tiffany, Assistant Director
Mr. E. P. Fortson, Jr., Chief, Hydraulics Division
Mr. G. B. Fenwick, Chief, Rivers and Harbors Branch
Mr. H. B. Simmons, Chief, Estuaries Section
Mr. T. J. Kinzer, Engineer, Estuaries Section
Mr. W. H. Bobb, Engineer, Estuaries Section

2. The conferences were opened at 9:30 a. m. on 12 February by Mr. Fortson, Chairman, who emphasized that the primary purposes of the conferences were to (a) review the present status of flushing theories, (b) review the results of previous prototype and laboratory investigations of flushing of estuaries, including the study by the Navy Hydrographic Office, and (c) draft up a detailed program of investigation to permit fulfillment of the requirements set forth in paragraphs 4 and 6 of Office, Chief of Engineers, letter of 16 December 1952, subject: "Flushing of Estuaries."

3. Mr. Simmons discussed the interest of the Corps of Engineers in flushing of estuaries, using as background material Waterways Experiment Station letter dated 25 March 1952, subject: "Flushing of Estuaries."

4. The consultants presented a brief discussion of the development and accuracy of existing flushing theories. In general, these theories are based on the concept that a net seaward movement exists in most

estuaries because of fresh-water inflow, and the rate of such movement may be computed from measurements of fresh-water discharge, tidal prism, volume of estuary, cross-sectional area, etc. For necessary simplification, the theories assume complete mixing and uniform flow from surface to bottom and bank to bank. Since the effects of islands, navigation facilities, irregular cross sections, and other physical features tend to prevent uniform flow, and since practically all estuaries of interest to the Corps of Engineers are known to be partially stratified vertically and/or laterally instead of being completely mixed, the consultants were of the opinion that existing theories are not sufficiently realistic to permit analytical determination of the flushing characteristics of estuaries at the present time. In addition to the above cited shortcomings of existing flushing theories, the consultants expressed the opinion that the size and interrelationship of the turbulent eddy system which controls salinity distribution in an estuary is not necessarily the same as that which controls movement and dispersion of a contaminant in the estuary. Dr. Pritchard agreed to prepare a more detailed statement as to the present status of flushing theories, with special emphasis as to their inadequacy in permitting analytical solutions of flushing problems of interest to the Corps of Engineers. Dr. Pritchard's statement will become a part of this record as soon as it is available, and copies of the statement will be furnished to all concerned.

5. The results of previous laboratory and field investigations of flushing of estuaries were discussed in considerable detail. Preliminary laboratory experiments of flushing of estuaries have been made by the Woods Hole Oceanographic Institute, and by this office under sponsorship of the Navy Hydrographic Office, while field investigations have been made by the Navy Hydrographic Office and the Chesapeake Bay Institute. Laboratory experiments made by Woods Hole were carried out in a short flume and were concerned only with certain basic dynamics of estuary flow, while the experiments carried out at this office were made in the Delaware River model. The results of these experiments have provided some valuable information relative to flushing characteristics. For example, the results of the investigations made at this office (the WES) indicate that use of the salinity distribution of an estuary as an index to its

flushing characteristics, and of the mean movement of a particle of fresh water through the estuary as an indication of the time required for flushing of a contaminant, probably do not constitute a correct approach to the latter problem. A possible reason for these discrepancies is that the size and interrelationship of the turbulent eddy system which controls salinity distribution is not necessarily the same as that which controls movement and dispersion of a contaminant. The salinity distribution of an estuary may be regarded as a steady-state condition, while the movement and dispersion of a contaminant in the estuary may be regarded as a transient condition superimposed upon the steady-state condition of salinity distribution. The consultants expressed the opinion that the results of field investigations made to date, or now in progress, will eventually prove to be extremely useful in determining the flushing characteristics of specific estuaries. However, until sufficient laboratory experiments have been made to develop an understanding of the influence of various parameters and to permit development of analytical methods for computing flushing characteristics, field data alone will be of little or no use in the solution of flushing problems.

6. The discussions summarized in the preceding paragraphs indicated that the objectives of the Corps of Engineers investigation of flushing of estuaries would not duplicate or conflict with those investigations carried out or in progress by the Navy Hydrographic Office or others. The objectives of the Corps of Engineers investigation are:

a. To explore the basic fundamentals of flushing of estuaries in an attempt to develop accurate analytical methods for determining the flushing characteristics of those estuaries being maintained for navigation and other purposes by the Corps of Engineers. The purposes of this phase of the investigation are (1) to permit reasonably accurate computation of the dispersion, dilution, or accumulation of contaminating agents introduced into estuaries by natural or man-made processes, and (2) to permit accurate computation of the effects of proposed changes in the physical characteristics of estuaries on their flushing characteristics.

b. To obtain sufficient empirical data from existing hydraulic models of important estuaries to provide (1) an interim analysis of the flushing characteristics of those important estuaries for which existing hydraulic models are available, and (2) a means for quickly evaluating the effects of salinity distribution, fresh-water discharge, tidal range,

location of release of contaminant, dimensions of contaminated area, and possibly other physical and hydraulic features on the flushing characteristics of such estuaries.

7. The question of whether it would be best to carry out the two phases described above in sequence or simultaneously was discussed. Colonel Dunn expressed the opinion that it would be best to carry out the two phases in sequence from a scientific viewpoint, since empirical results of flushing tests in existing models would logically be used to check the validity of flushing equations developed during the first phase of the investigation. However, he felt that this procedure would require too great a length of time. Furthermore, the results of flushing tests in existing models may prove useful in defining the most important hydraulic and physical factors which influence flushing and therefore result in prosecution of the first phase of the investigation in a more logical and orderly manner. It was therefore agreed that the two phases of the investigation would be carried out simultaneously. A third phase of the investigation, which can only follow completion of the two phases described above, will consist of application of the results of the laboratory investigations described herein to prototype estuaries, for which models are not available, in order to define their flushing characteristics. Plans for carrying out this phase of the over-all investigation will be made when and if the results of the investigation described herein indicate that development of accurate analytical methods for determining flushing characteristics of estuaries is assured.

8. The program of investigation agreed upon as being the minimum required to attain the objectives of the study is outlined in paragraphs 5-9 of the main report. The program consists of two parts, which will be carried out simultaneously to fulfill the requirements set forth in paragraph 7 above. The two parts of the program consist of: (a) a total of 31 tests in models of hypothetical idealized estuaries to provide data required to evaluate the effects of degree of stratification, geometry of estuary, scale effects in transferring model flushing data to the prototype, and to provide quick and approximate answers to flushing problems for those estuaries for which models are not available; and (b) a total of 34 tests in existing models of the Delaware River and Charleston

Harbor to afford an interim analysis of the flushing characteristics of these specific estuaries and to permit quick evaluation of the effects of tidal amplitude, fresh-water discharge, location and size of contaminated area, tidal planes, and possibly other physical and hydraulic factors on flushing characteristics. Analyses of the results of model tests will be made as quickly as possible as they are conducted, and development of analytical methods for computing flushing characteristics will be carried forward as an integral part of the investigation. The specific test program outlined in the main report may be modified from time to time if parallel work on the development of flushing equations should indicate that such modification is required.

9. The consultants were questioned as to whether they would provide direct assistance in the analysis of results of model flushing tests and development of analytical methods for computing the flushing characteristics of estuaries. All agreed that their services would be available in these respects, as required by the Waterways Experiment Station throughout the course of the investigation. Their opinions were also requested as to the usefulness, feasibility, and prospects for success of the investigation. It was their unanimous opinion that the program of investigation outlined herein will provide the best possible means for solving those flushing problems of interest to the Corps of Engineers. They were also of the opinion that no other flushing study carried out to date or now in progress would provide such information, and that no other institution in this country had the required personnel and facilities to carry out so complete an investigation of this nature.